Overview of the NASA Subsonic Rotary Wing Aeronautics Research Program in Rotorcraft Crashworthiness

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Abstract

This paper provides an overview of rotorcraft crashworthiness research being conducted at NASA Langley Research Center under sponsorship of the Subsonic Rotary Wing (SRW) Aeronautics Program. The research is focused in two areas: development of an externally deployable energy attenuating concept and improved prediction of rotorcraft crashworthiness. The deployable energy absorber (DEA) is a composite honeycomb structure, with a unique flexible hinge design that allows the honeycomb to be packaged and remain flat until needed for deployment. The capabilities of the DEA have been demonstrated through component crush tests and vertical drop tests of a retrofitted fuselage section onto different surfaces or terrain. The research on improved prediction of rotorcraft crashworthiness is focused in several areas including simulating occupant responses and injury risk assessment, predicting multi-terrain impact, and utilizing probabilistic analysis methods. A final task is to perform a system-integrated simulation of a full-scale helicopter crash test onto a rigid surface. A brief description of each research task is provided along with a summary of recent accomplishments.

Introduction

In 2005, the NASA Aeronautics Program went through a major overhaul of its research programs to focus the work on foundational physics and fundamental research in four flight regimes: hypersonics, supersonics, subsonic fixed wing, and subsonic rotary wing. Three guiding principles were established and used to rescope the program: 1. NASA is dedicated to the mastery and intellectual stewardship of the core competencies of Aeronautics for the Nation in all flight regimes, 2. The research will be focused in areas that are appropriate to NASA's unique capabilities, and 3. Research will be conducted to address the fundamental needs of the Next Generation Air Transportation System (Porter, 2007). A four-step process was implemented in 2005-2006 to *assess* long-term research goals within each flight regime, *solicit* industry input regarding opportunities for cooperative partnerships, *review* submitted proposals, and *request* additional proposals from universities for research in foundational physics. As part of this process, several research proposals on rotorcraft crashworthiness were submitted, reviewed, and funded

by the Subsonic Rotary Wing (SRW) Aeronautics Program. The objective of this paper is to provide an overview of ongoing research in this topic area.

Since its inception in 2006, the NASA SRW Aeronautics Program in Rotorcraft Crashworthiness has focused attention on two main areas of research: development of an externally deployable energy absorbing (DEA) concept and improved prediction of rotorcraft crashworthiness. The DEA concept is a composite honeycomb structure that can be deployed to provide energy attenuation, much like an external airbag system (Kellas *et al*., 2007). The second main research area relates to crash modeling and simulation. Several research topics have been identified to achieve improved prediction of rotorcraft crashworthiness, including: occupant modeling and injury prediction, multi-terrain impact simulation, model validation studies that focus on probabilistic analysis, and development of system-integrated simulation models. This paper will present an overview of these research tasks including the accomplishments, ongoing work, and planned activities.

Development of a Deployable Energy Absorber (DEA)

A task was initiated to develop a DEA that utilizes an expandable honeycomb-like structure to absorb impact energy by crushing (Kellas 2004 and Kellas *et al*., 2007). The new concept is based on a unique and patented flexible hinge at each junction of its cell walls. This feature enables almost any size and strength energy absorber to be fabricated and readily deployed. Like conventional honeycomb, once expanded, the energy absorber is transformed into an efficient orthotropic cellular structure, with greater strength and stiffness along the cell axis as compared to the transverse directions. Typically, the hinge consists of a fabric made of relatively strong, stiff, and tough fibers such as Kevlar™. Other flexible materials can also be used for the construction of the hinges; however, advanced fiber reinforced fabrics are thought to offer some unique opportunities for structural tailoring.

The flexible hinge enables various methods of expanding the cellular structure with the most basic ones shown in Figure 1. The linear expansion mode, shown in Figure 1(a), represents the simplest mode. When expanded in this fashion, the DEA produces higher specific energy absorption due to a more efficient volumetric expansion (lower effective expanded density). However, radial deployment, which is illustrated in Figure 1(b), produces an energy absorber with better omni-directional capability. To minimize the expanded density of the energy absorber, the cells are tapered, as shown in Figure 1(b). Because most practical applications involve curved rather than flat surfaces, the two basic deployment methods can be combined into a hybrid approach.

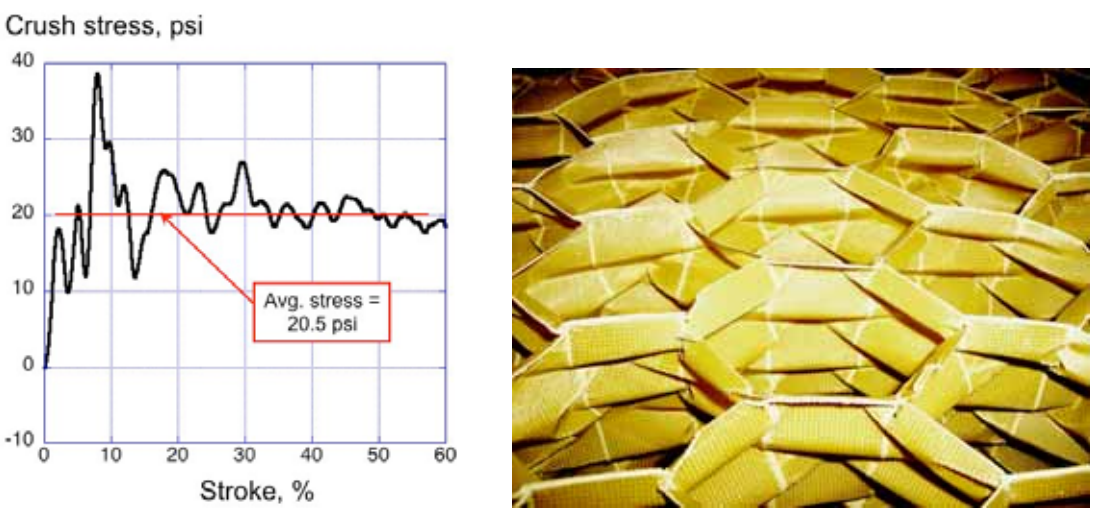
Typical results from an impact test of a composite energy absorber are shown in Figure 2. For this test, a steel block weighing 477.2-lb impacted a 104-cell DEA component at 22.2-fps. The DEA was fabricated of Kelvar™-129 fabric with a ±45° orientation relative to the vertical or loading direction. Nominal cell width was 1.0-in. and cell wall thickness was 0.01-in. The DEA was 10-in. high, 21-in. long, and 15.75-in. wide, and was designed to achieve an average crush stress of 20-psi. The plot of Figure 2(a) shows

dynamic crush stress versus stroke data obtained from the impact test. An average crush stress of 20.5-psi was obtained for a crush stroke of 60%. Typical stroke efficiencies of between 75 and 85% are observed for fully compressed DEA components. Note that the area under the curve shown in Figure 2(a) is proportional to the amount of kinetic energy dissipated through crushing of the energy absorber. A post-test photograph is shown in Figure 2(b) that depicts the deformation modes exhibited by the DEA during crushing. The primary mechanisms for energy dissipation are local buckling, tearing, and delamination.

Several additional component tests were performed, as described in the paper by Kellas *et al*. (2007), including off-axis tests in which the cells of the DEA were oriented at 27° to the loading axis. These tests were conducted to examine the shear properties and structural stability of the DEA for off-axis loading conditions. One area of ongoing work is the development of a shell-based finite element model of the DEA that accurately predicts the crushing response and deformation modes observed experimentally. In addition, further testing is planned to evaluate the externally deployed concept for combined velocity conditions, including a high forward component, which will apply considerable shear loads to the DEA. If the development program is successful, the DEA may prove to be a viable alternative to external airbag systems for improving the crashworthiness of existing helicopters.

(a) Linear deployment. **(b) Radial deployment.**

Figure 1. Photographs showing deployment methods of the DEA.



(a) Dynamic crush response. **(b) Post-test photograph.**

Figure 2. Test data for deployable honeycomb specimen.

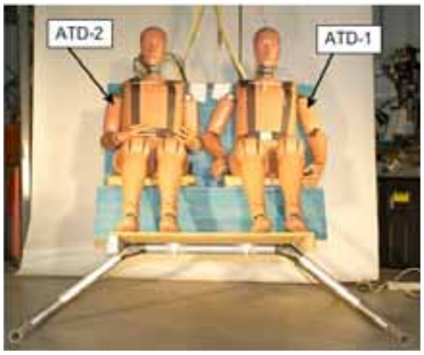
Improved Prediction of Rotorcraft Crashworthiness

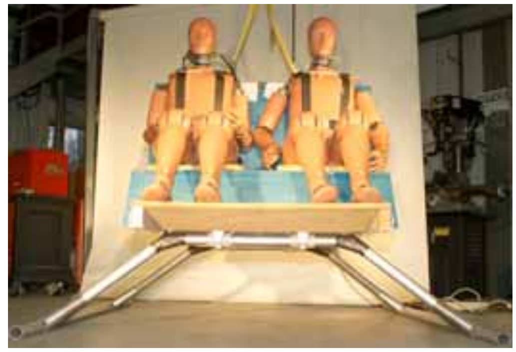
The current generation of commercial nonlinear, explicit transient dynamic finite element codes, such as LS-DYNA (Hallquist, 2007), are capable of accurately simulating airframe structural response to crash impact. However, analytical models need to be thoroughly validated so that designers have greater confidence in the analytical results, thus encouraging use of crash simulation during the preliminary design phase. In 1992, a Workshop on Computational Methods for Crashworthiness (Noor *et al.*, 1992) was held on September 2-3, 1992, at NASA Langley Research Center, Hampton, Virginia. Attendees were asked to identify key technology needs for improved crash modeling and simulation. Their list was grouped under five main headings including (1) understanding the physical phenomena associated with crash events, (2) high-fidelity modeling of the vehicle and the occupant during crash, (3) efficient computational strategies, (4) test methods, measurement techniques, and scaling laws, and (5) validation of numerical simulations. Many of the key technology needs identified during the workshop are still valid today. Consequently, the current SRW research program for improved prediction of rotorcraft crashworthiness was planned and implemented to address these topic areas.

Occupant Modeling and Injury Prediction

In 2006, NASA performed a series of vertical drop tests of a redesigned skid gear for use on the WASP kit-built helicopter, which is marketed by HeloWerks, Inc. of Hampton, Virginia. The test article consisted of a skid gear mounted beneath a steel plate. A seating platform was attached to the upper surface of the steel plate, and two 95th percentile Hybrid III male Anthropomorphic Test Devices (ATDs) were seated on the platform and secured using a four-point restraint system. An opening was cut into the seat platform to allow space for seat foam filler. The foam filler space on the left side of the platform was filled with several layers of Styrofoam. On the right side, three blocks of polyisocyanurate foam were used. The test program provided an excellent opportunity to conduct high fidelity modeling of the vehicle and occupant, specifically examining the occupant models available within LS-DYNA (Jackson, *et al.*, 2007).

A series of three vertical drop tests were conducted at 8.4- 10.0- and 12.7-fps to qualify the final skid gear design. A pre-test photograph of the test article, which weighed 1,060 lb, is shown in Figure 3(a). Note that the dummy occupant designated ATD-1 is seated on the Styrofoam layers on the left side of the seating platform and ATD-2 is seated on the polyisocyanurate foam blocks on the right side of the seating platform. The drop test was conducted by lifting the test article to a height of 13 in. and releasing it to impact a smooth concrete surface at 8.4-fps. The average measured spread of the skid gear was 4.4 inches. A post-test photograph of the test article is shown in Figure 3(b). Damage was observed to the metal saddles surrounding the attachment of the struts to the skid beams. This damage consisted mainly of buckling of the metal saddle, as shown in Figure 4(a). No cracks or rivet failures were observed. In addition, no crushing of the seat foams was observed. The vertical acceleration responses of the left side, middle, and right side of the seat platform are shown in Figure 4(b). The three curves are nearly identical, each exhibiting three peaks ranging in magnitude from 4.7 to 7.7 g.



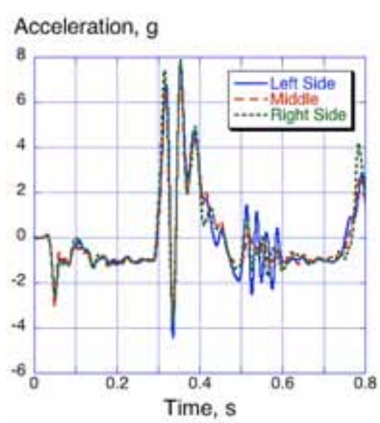


(a) Pre-test photo. **(b) Post-test photo.**

Figure 3. Pre- and post-test photographs of the 8.4-fps vertical drop test.

The LS-DYNA finite element model of the skid gear test article is shown in Figure 5. Details of the model are described in the paper by Fuchs *et al.*, (2008). A linear elastic-plastic material model was defined for the aluminum representing the skid gear saddles and an elastic model was defined for the remainder of the skid gear and steel plate. The skid gear was modeled using circular cross-section beam elements of varying thickness. The seat foam fillers were represented using solid elements that were assigned a material model in LS-DYNA designated *MAT_CRUSHABLE_FOAM. Material characterization testing was performed to evaluate the behavior of the two seat foams, Styrofoam and polyisocyanurate. The test data were used as input for the material model.

Two Hybrid III 95th percentile male occupants were inserted into the structural model using the *COMPONENT_HYBRIDIII command in LS-DYNA. These models represent the human body using rigid links, surrounded by ellipsoids, with kinematic joints that mimic the motion of the human body. Seatbelt elements were used to constrain the motion of the occupant models. Also, contact surfaces were defined to represent contact between the skid gear and the impact surface, between the occupants and the seatbelts, and between the occupants and the seating platform. The model was executed in LS-DYNA version 971 on a Linux workstation computer with a single processor for 0.2 seconds, which required 7 hours and 45 minutes CPU.



(a) Photo depicting saddle buckling. **(b) Seat platform accelerations.**

Figure 4. Skid gear drop test results.

Comparisons of the filtered pelvic acceleration responses of the left and right ATD dummy occupants with LS-DYNA analytical predictions are shown in Figure 6. The analytical results accurately predict the peak acceleration values, as well as the general acceleration trends. The findings from this research task provide confidence in the use of LS-DYNA occupant models (Fuchs *et al*., 2008). In the future, these models will be used in the development of a system-integrated simulation of a full-scale helicopter crash. Currently, work is ongoing to fully evaluate different LS-DYNA occupant models.

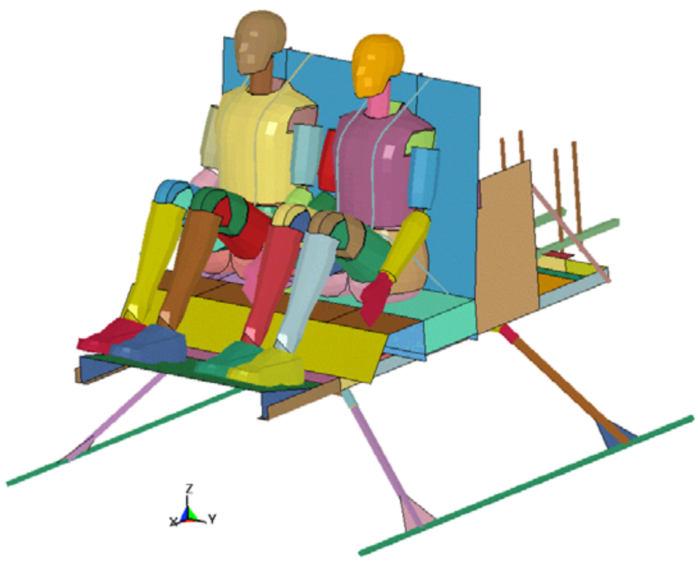
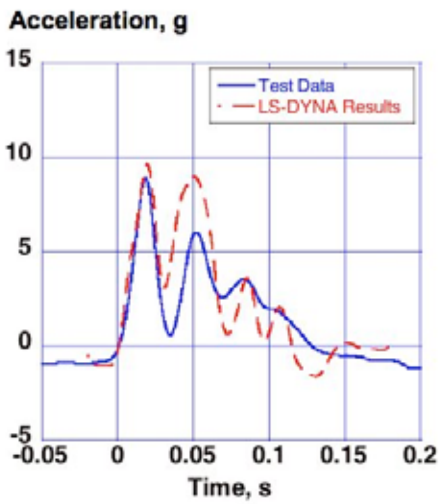


Figure 5. LS-DYNA model of the skid gear with occupants.

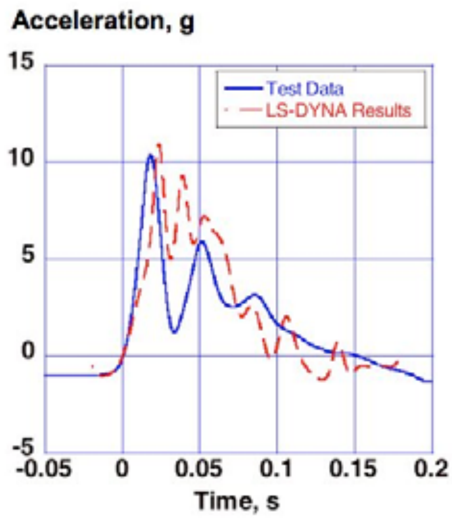
The dynamic acceleration responses obtained from the instrumented ATDs were used to perform an injury risk assessment based on the Dynamic Response Index (DRI) (Stech *et al*., 1969), and the Brinkley Index (Brinkley *et al.*, 1989). The results indicate that the potential of injury for each of the three impact test conditions is extremely low. The maximum value of DRI obtained was 15.4. Operational data from actual ejection seat incidents indicate that the spinal injury rate for a maximum DRI value of 15.4 is less than 0.5% percent. Likewise, only one low-risk Brinkley Index curve exceeded a magnitude of 1.0. This curve was for the chest of ATD-1 for the 12.7-fps vertical drop test. The medium-risk curve for the chest of this occupant did not exceed 1.0. Therefore, the maximum possible risk of injury would be considered between low-to-medium. All other Brinkley Index curves were well below a magnitude of 1.0. Additional information on the injury assessment may be found in the paper by Jackson *et al.* (2007).

Multi-Terrain Impact Simulation

Vertical drop tests of a 5-ft-diameter composite fuselage section (Jackson, 2001) retrofitted with four blocks of the DEA were conducted onto a rigid surface (concrete), soft soil (sand) and water. The purpose of the experimental program was twofold: to evaluate the energy absorption performance of the DEA for multi-terrain impact and to generate test data for validation of numerical models.



(a) Left side ATD.



(b) Right side ATD.

Figure 6. Test analysis correlation of pelvic acceleration responses for the ATD dummies during the 8.4-fps vertical drop test.

Rigid Surface Impact

A vertical drop test of the composite fuselage section retrofitted with four blocks of the DEA was conducted successfully onto a rigid surface using the 70-ft Vertical Drop Tower located at NASA Langley. A pre-test photograph of the test article is shown in Figure 7(a). To ensure fuselage survivability for use in subsequent tests, the open section was stiffened by a pair of ±45° woven glass straps. Ten 100-lb lead masses were secured to the fuselage floor through standard seat rail fasteners, five masses per side. The total fuselage section weighed 1,212-lb and each energy absorber contributed 5.6-lb. The energy absorbers were fabricated of a single woven-ply of Kevlar™-129 and had dimensions of 20-in. tall, 16.5-in. wide and 20.5-in. deep. Note that the bottom surfaces of the DEA blocks were curved to alleviate the large load spike upon impact. The energy absorbers were sized to provide an average floor-level acceleration of 20-g. Accelerometers were mounted in the center of selected lead masses on the floor to record dynamic structural responses during impact. The drop test was performed by releasing the test article from a height of 23-ft to impact a concrete surface at 38.4-fps.

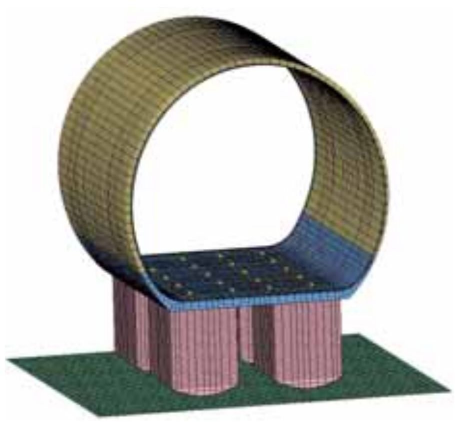
A post-test photograph of the fuselage section following rigid surface impact is shown in Figure 7(b). No damage to the upper fuselage section or floor was observed post-test. Based on double integration of the floor-level acceleration data, the DEA crushed 14-in., which was 70% of the maximum available stroke. An average acceleration of 19.4-g was recorded on the floor.

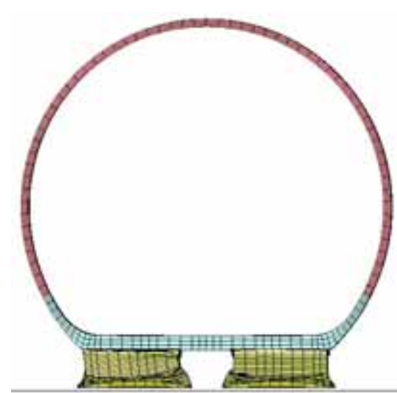
Predictions were generated from an LS-DYNA simulation of the 38.4-fps vertical drop test of the composite fuselage section retrofitted with four DEA blocks. For this initial simulation, the DEA were modeled using solid elements with material properties defined using component crush test data. The model, shown in Figure 8(a), was executed for 0.15 seconds using LS-DYNA v971, requiring 7 hours and 30 minutes of total CPU time.

(a) Pre-test photo. **(b) Post-test photo.**

Figure 7. Pre- and post-test photographs of composite fuselage section with DEA.

A picture of the deformed model is shown in Figure 8(b) at 0.072 seconds, which is close to the end of the primary impact event. Some significant differences are observed in how the energy absorbing blocks behave during impact. For the test, the cell walls within the composite honeycomb structure fold sequentially forming an accordion-like deformation pattern, as shown in Figure 7(b). The progressive folding initiates at the point of impact. Following the test, elastic energy, which is a small portion of the total energy, is released providing some rebound velocity. For the model, the energy absorber shows element compression initiating in the area of contact with the impact surface and at the top of the foam blocks. Early in time, the crushing and compression of the solid elements occurs in a stable manner; however, eventually the blocks buckle as a result of uneven compressive loading. Very little rebound of the model is observed.





(a) LS-DYNA model. **(b) Front view of the model at 0.072 s.**

Figure 8. LS-DYNA finite element model of the vertical fuselage drop test.

Comparisons of filtered analytical and experimental acceleration-time histories are shown in Figure 9 for the center lead mass on the right side. The analytical acceleration response shows excellent agreement with the experimental curve for the first 0.03 seconds, accurately predicting the magnitude and timing of the peak acceleration (30-g). Following the initial peak, the model predicts two additional peaks of lower magnitude (25-g) than the first. The predicted response had an average acceleration of 22.7-g,

which is approximately 17% higher than the test average of 19.4-g. Additional information on the drop test, model development, and test analysis correlation may be found in Kellas *et al*. (2007).

Results from the successful drop test of a retrofitted composite fuselage section onto a rigid surface indicated that the energy absorbers removed almost all of the kinetic energy of the impact event. Despite the 38.4-fps impact velocity, no damage to the upper cabin or floor of the fuselage section was observed. Average floor-level accelerations were approximately 19.4-g's. In comparison, for an impact of only 31-fps an average floor-level acceleration of 29.9-g was obtained from a previous test of a similar fuselage section with a more conventional foam-filled subfloor (Lyle *et al*., 2002). Moreover, the foam-filled subfloor used in the previous tests was 8% heavier than the deployable honeycomb energy absorbers.

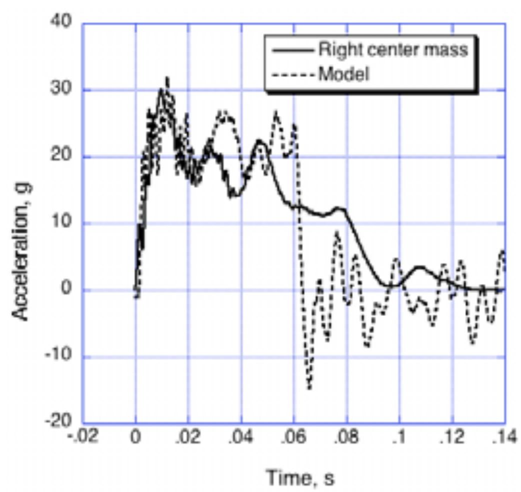
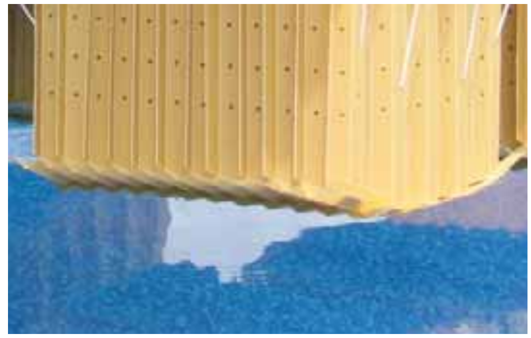


Figure 9. Comparison of experimental and analytical acceleration responses.

<u>Water Impact</u>
In May 2007, a 25-fps-water impact test of a composite fuselage section with deployable energy absorbers was conducted successfully using the 70-ft Vertical Drop Tower located at NASA Langley. This drop test was conducted to evaluate the energy attenuation capabilities of the deployable concept for water impact and to generate test data for correlation with analytic models. More details on this test are reported in the paper by Kellas *et al.* (2008). A 15-ft-diameter pool, filled to a height of 42 inches, was located beneath the drop tower. The fuselage section consisted of an upper cabin and floor, with four DEA mounted beneath the floor, as shown in Figure 10(a). Note that for water impact, the DEA were fabricated to incorporate a single-ply Kevlar™ layer covering the bottom surface. A photograph of the cover is shown in Figure 10(b). Ten 100-lb lead blocks were attached to the floor through seat rails, five per side. The total weight of the test article was approximately 1,225 lb. Test data indicate that peak floor-level accelerations were less than 20-g, even though minimal crushing of the DEA was observed.

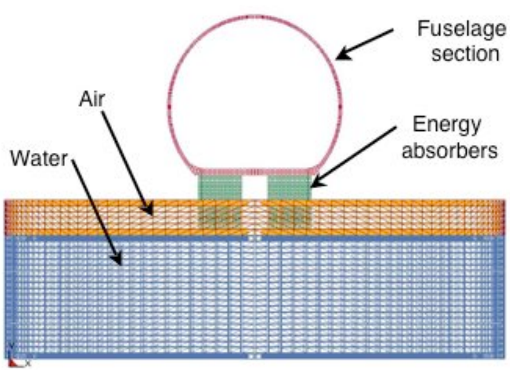


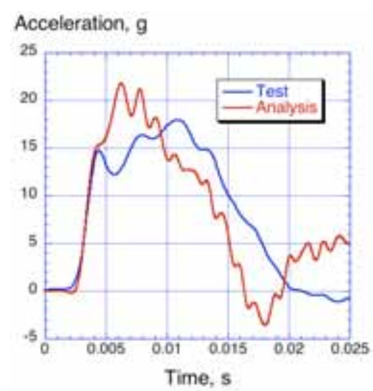
(a) Pre-test photo. **(b) Close-up view of the bottom cover.**

Figure 10. Pre-test photographs of the water impact test.

The water impact was simulated using both Arbitrary Lagrange Euler (ALE) and Smooth Particle Hydrodynamics (SPH) approaches in LS-DYNA. Analytical predictions were correlated with experimental data obtained during the drop test. In both the ALE and SPH simulations, the same Lagrangian model of the fuselage section was used, as described in Kellas *et al*. (2007). The ALE model and acceleration predictions plotted with test data are shown in Figure 11. The simulation accurately predicts the onset rate of the acceleration response, but over predicts the peak magnitude (22-g for the analysis and 18-g for the test).

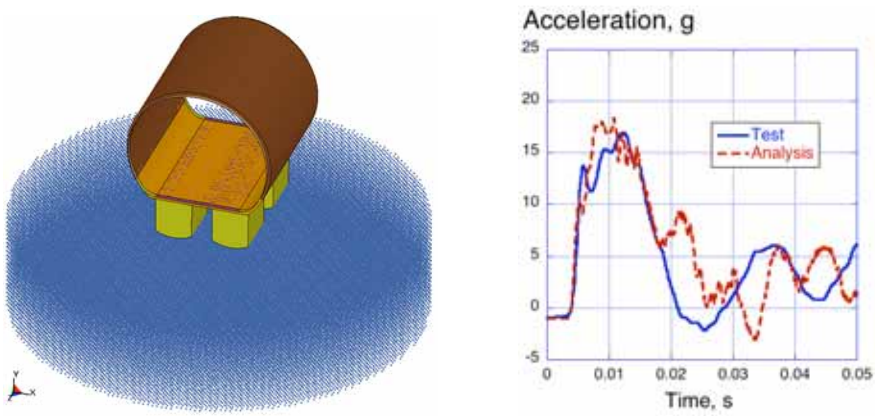
The SPH model with 2-in. mesh spacing is shown in Figure 12(a) along with a comparison of analytical predictions of floor-level acceleration response correlated with test data. The model consisted of 129,128 SPH elements, which required 29 hours to simulate 50 ms. A mesh discretization study was conducted that demonstrated best correlation with a 2-in. mesh spacing. Initially, a 3-in. mesh spacing SPH model was executed in which the analytical results under predicted the test data. Subsequently, a 1.5-in. mesh spacing model was developed that over predicted the tests results. Consequently, the 2-in. mesh SPH model was developed and executed. This simulation shows excellent agreement with the test data, as shown in Figure 12(b). These results demonstrate the importance of mesh discretization studies when using the SPH method for simulating water impact.





(a) ALE model. **(b) Test-analysis correlation.**

Figure 11. ALE model and pre-test predictions correlated with test data.



(a) SPH model with 2-in mesh. **(b) Test-analysis correlation.**

Figure 12. SPH model and pre-test predictions correlated with test data.

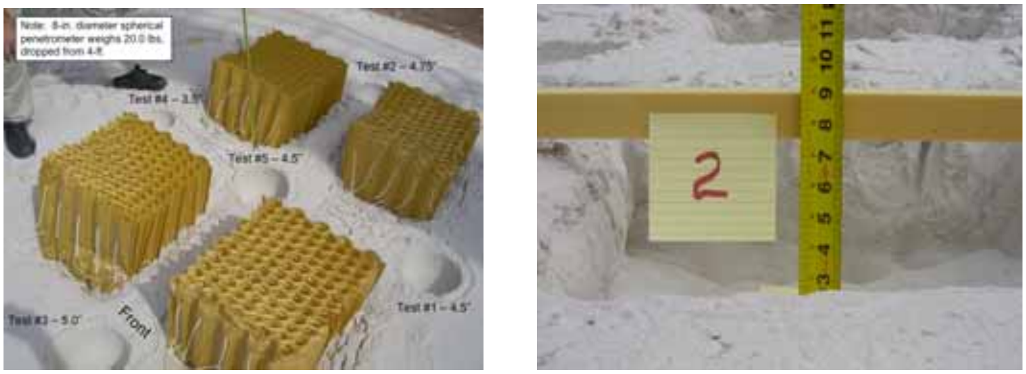
<u>Soft Soil Impact</u>

As a final evaluation, the composite fuselage section retrofitted with four blocks of the DEA was impacted onto soft soil (sand) at 37.4-fps, as reported in Kellas *et al*. (2008). A 15-ft x 15-ft wooden box was built and located beneath the drop tower. The box was filled to a height of 2.5-ft with high-grade sifted sand. The fuselage section was configured in the same manner as for the two previous tests onto rigid surface and water. Pre- and post-test photographs of the test article are shown in Figure 13.

Following the impact test, the deployable energy absorbers were separated from the fuselage section to enable easier measurement of crater depths. Also, penetrometer tests were made at several locations to characterize the material properties of the sand. These tests involved dropping a 20-lb hemisphere that was instrumented with tri-axial accelerometers from a height of 4 feet onto the sand. A photograph showing the penetrometer test locations is provided in Figure 14(a). Following the penetrometer tests, the deployable energy absorbers were removed from the sand and post-test measurements of the depth of the impressions left in the sand were made. A photograph illustrating the measurement technique is shown in Figure 14(b). It was determined that the maximum crater depths ranged from 7 to 9 inches.

(a) Pre-test photo. **(b) Post-test photo.**

Figure 13. Photographs from the drop test onto sand.



(a) Penetrometer test locations. **(b) Crater depth measurement.**

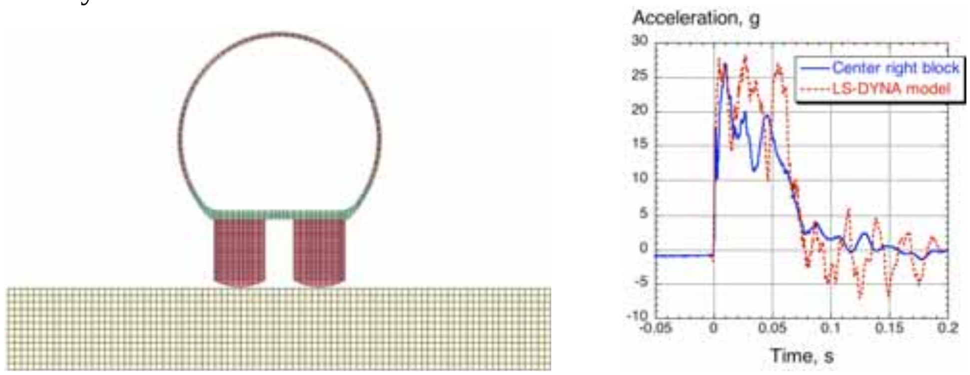
Figure 14. Photographs illustrating post-test measurement techniques.

The sand impact test was simulated using LS-DYNA. The model is shown in Figure 15(a). The fuselage section model is the same as used in previous impact simulations. A 15-ft by 15-ft by 2.5-ft block of sand was modeled using solid elements. The material properties assigned to the sand were obtained from a model that was developed in 2001 for correlation with test data obtained in a drop test onto a similar type of sand (Fasanella *et al.*, 2005). One major difference between the two tests, however, was that the sand used in the 2001 test was packed. The sand in the current test was loose and unpacked. Analytical and experimental acceleration-time histories are plotted in Figure 15(b). The analysis accurately predicts the onset rate of acceleration and the magnitude and timing of the initial peak of the acceleration response, up to 0.035 s. After this time, the level of correlation is diminished. In general, the results indicate that the material properties used for the sand are too stiff. The model will be revised to incorporate the actual sand properties determined from the penetrometer tests and to account for a slight pitch attitude of the test article.

Probabilistic Analysis

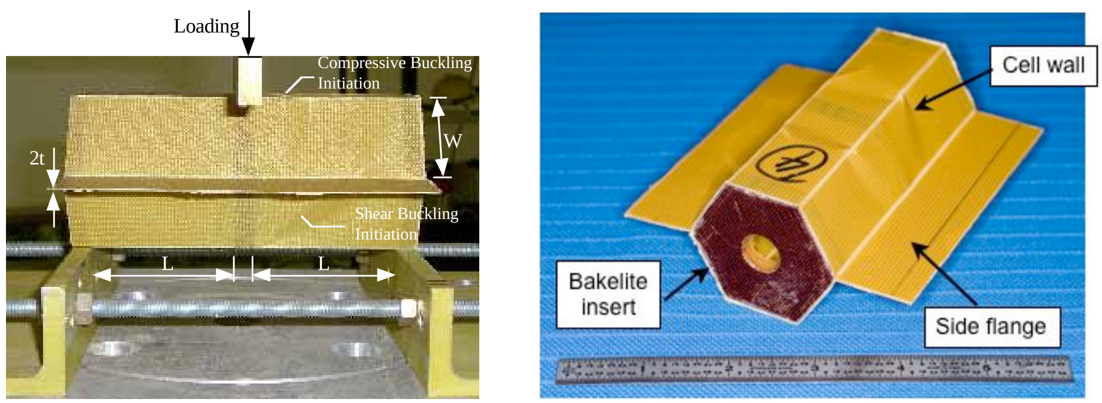
One roadblock to the development of a robust shell-based model of the DEA is determining an accurate material model for Kevlar™-129 fabric. To resolve this problem, three-point flexure tests were performed on a series of single hexagonal cells fabricated of Kevlar™-129. Each test article consisted of the hexagonal cell, two side flanges, and three Bakelite stanchions located at each of the loading points. The role of the stanchions, which were bonded to the cell walls, was to preserve the hexagonal shape of the cell while distributing the load uniformly over the entire perimeter of the cell. To eliminate possible trapped air effects during loading, each stanchion was perforated. The test set-up is shown in Figure 16(a) and a typical single-cell test article is shown in Figure 16(b). Dimensions of the specimens and maximum average load values are listed in Table 1 for four single cell configurations of increasing width. Because of fabrication irregularities, geometric eccentricities, and material property uncertainties, the problem of reconciling analytical models with experimental data is a challenge. A first look at the correlation results between single cell load/deflection data with LS-DYNA predictions showed problems (Kellas *et al.*, 2007), which prompted additional work in this area. A computational approach was implemented that uses analysis of variance, deterministic

sampling techniques, response surface modeling, and genetic optimization to reconcile test with analysis results.



(a) LS-DYNA model of sand impact. **(b) Acceleration responses.**

Figure 15. LS-DYNA model of sand impact.



(a) Photo of bend test configuration. **(b) Three-quarter view of a single-cell test article.**

Figure 16. Photographs of the three-point flexure test and single-cell specimen.

No. of Samples	Width (in)	Length (in)	Thick (in)	Rate (ipm)	Max Avg Load (lb)
5	.75	3.35	.01	2.0	216.9
5	1.0	4.21	.01	2.0	200.8
5	1.25	5.10	.01	2.0	213.9
5	1.5	5.95	.01	2.0	205.2

Table 1. Specimen dimensions and average load values.

LS-DYNA simulations of the three-point-bend test of the single-cell specimens were performed with the objective of optimizing material input properties through model calibration. Verified material properties obtained from the single cell simulations will be used as input to more complex simulations of the composite energy absorbers. The LS-DYNA finite element model of the single cell (w=1.0-in.) is shown in Figure 17. The model consists of three parts including the cell wall (t=0.01-in.), the side flanges (t=0.02-

in.), and three 0.25-in.-long Bakelite stanchions. The complete model consisted of 27,098 nodes; 12,000 hexagonal solid elements; and 13,600 Belytschko-Tsay shell elements. The simple support end conditions were represented by single point constraints applied to a line of nodes on both ends of the specimen. Load was applied to a set of top center nodes using the *LOAD_NODE_SET command in LS-DYNA. A complete description of the model along with preliminary test-analysis correlations can be found in Kellas *et al.* (2007).

The process of reconciling the model to generate updated material property values is described, as follows. The initial step in the probabilistic approach was to identify upper, lower, and nominal values for the *MAT_LAMINATED_COMPOSITE_FABRIC material card (MAT 58) that was used to represent the Kevlar™-129 fabric. The nominal values were based on tensile test data of ±45° and 0°/90° coupons. These values are listed in Horta *et al.* (2008). Using these bounds, uncertainty propagation is conducted by creating a population of parameters uniformly distributed over their ranges and executing multiple LS-DYNA simulations. Analytical results are subsequently assembled into a response surface model and used to compute the total stress variance and the stress variance per parameter. Interestingly, for this problem it was found that one set of parameters was important at low strain levels, whereas a different set of parameters was important at higher strain levels. The response surface model used for this assessment is based on Kriging's Method (Sacks *et al.*, 1989 and Krishnamurthy, 2005). Adequacy of the technique was judged based on its ability to not only provide exact matching of LS-DYNA solutions but also on its ability to accurately interpolate solutions of known surfaces.

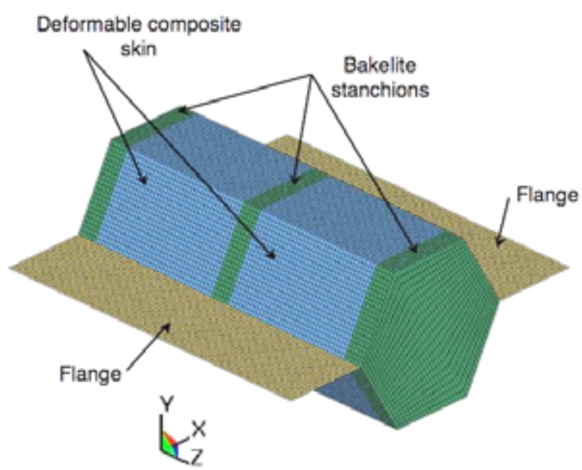


Figure 17. Single cell model for 3-point-bend test.

With a parameter set at hand and the variance analysis completed, the next step is to reconcile the test data with the analysis. Response surface surrogate models were used with a genetic optimization algorithm to compute parameters to reconcile test data with LS-DYNA predictions. Because the response surface model is constructed using a limited number of LS-DYNA solutions, a reconciling set of parameters can only be obtained using an iterative process. For example, after computing an optimal parameter set using a surrogate model, when the parameters are used in LS-DYNA the solution is only as good as the response surface prediction error, hence suboptimal. However, if the

new LS-DYNA solution obtained with the suboptimal parameters is used to rebuild the response surface model, the error can be reduced. As an example, the load/displacement curves are plotted in Figure 18 for test (single cell, w=1.0-in.), Kriging (KRG-Opt), and LS-DYNA mean value displacements with parameters computed from an optimization that incorporated 155 LS-DYNA solutions. The plot indicates that the Kriging (blue) and LS-DYNA (green) predictions are close to each other and to the test mean values in red. The nominal and KRG-optimal MAT 58 values are listed in Table 2.

This research task demonstrated promising results in the application of probabilistic methods to explicit transient dynamic simulations, as described in Horta *et al.* (2008). Initial analysis of variance was instrumental in understanding deficiencies in the modeling approach and the correlation results showed significant reduction in error. In the future, similar approaches will be used to quantitatively assess the level of correlation between LS-DYNA predictions of a full-scale helicopter crash with test data, as described in the following section of the paper.

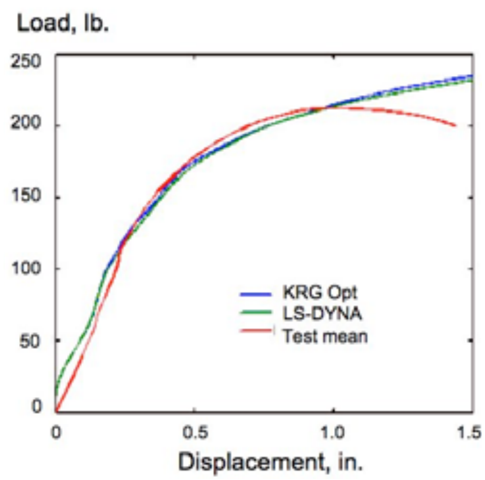


Figure 18. Test analysis correlation.

MAT 58 Parameter No.	Material Property	Nominal Value	Optimum KRG (155) Value
1	Stress limit of nonlinear portion of shear curve, psi	4156.3	7020.8
2	Strain limit of nonlinear portion of shear curve, in/in	0.022509	0.00935
3	Shear modulus, psi	4.563e+5	1.5374e+5
4	SLIMS	0.30087	0.1
5	ERODS	0.28554	0.73279
6	Strain at shear strength, in/in	0.053669	0.094463
7	Shear strength, psi	8077	12383
8	Young’s modulus longitudinal direction and transverse, psi	1.3183e+6	1.3e+006

Table 2. Nominal and optimized parameter values using the Kriging Method.

System-Integrated Helicopter Crash Simulation and Test

The plan for the NASA SRW Aeronautics Program in Rotorcraft Crashworthiness outlines a final research project with the following sub-tasks,

- Develop a system-integrated finite element model of a helicopter,
- Perform LS-DYNA analyses simulating the full-scale crash impact,
- Generate pre-test predictions,
- Conduct full-scale crash tests to obtain experimental data for model validation and to evaluate two different external energy attenuating systems,
- Assess test-analysis correlation using probabilistic methods
- Utilize the validated model to perform a complete risk assessment by evaluating different impact conditions, different impact attitudes, and multi-terrain.

The system-integrated helicopter model will include accurate physical representations of the impact surface, landing gear, airframe, seats, restraint systems, occupants, cargo, transmission ballast, and the external energy absorbing devices. Two full-scale crash tests are planned, one in which the helicopter is retrofitted with external airbags and the second with the helicopter retrofitted with the DEA.

The Boeing MD 530 helicopter, depicted in Figure 19, has been identified as the test article for this task. Boeing has conducted a preliminary evaluation of the application of external airbags for this vehicle through testing and LS-DYNA simulations as documented in the paper by Bolukbasi (2007). Two helicopters will be provided for the purpose of crash testing and model validation. Currently, the impact tests will be conducted onto a rigid surface at the Landing and Impact Research (LandIR) facility located at NASA Langley Research Center in Hampton, VA in 2009.

Figure 19. Photograph of the MD 530 helicopter.

Concluding Remarks

This paper has presented an overview of the ongoing research tasks in rotorcraft crashworthiness sponsored by the NASA Subsonic Rotary Wing Aeronautics Program. The research is focused in two areas: development of an externally deployable energy attenuating concept and improved prediction of rotorcraft crashworthiness. The deployable energy absorber (DEA) is a composite honeycomb structure, with a unique flexible hinge design that allows the honeycomb to remain flat until needed for deployment. The capabilities of the DEA were demonstrated through component crush

tests and vertical drop tests of a retrofitted fuselage section onto a rigid surface, water, and soft soil. Results of this testing, to date, indicate that the DEA is a structurally efficient energy attenuator with excellent multi-terrain capabilities.

The research on improved prediction of rotorcraft crashworthiness is focused in several areas including simulating occupant responses and injury risk assessment, predicting multi-terrain impact, and utilizing probabilistic analysis methods. A final task is to develop a system-integrated model of a full-scale helicopter, outfitted with two different external energy-attenuating devices, and generate pre-test predictions of the crash response. Accomplishments, plans, and ongoing research are described for each of these subtasks, as follows:

- Occupant responses were obtained from several vertical drop tests of a modified skid gear for the WASP helicopter. The data from this experimental program were used to successfully evaluate occupant models available within LS-DYNA. Ongoing research is being performed to evaluate additional LS-DYNA occupant models.

- For each of the multi-terrain impact tests that were conducted to evaluate the capabilities of the DEA, corresponding LS-DYNA simulations were performed. For the water impact, both Arbitrary Lagrange Euler (ALE) and Smooth Particle Hydrodynamics (SPH) methods were applied to simulate the fluid-structure interaction problem. In general, reasonable correlation was obtained and work is ongoing to refine the multi-terrain models to improve test-analysis correlation.

- Probabilistic methods were applied to develop a more accurate material model of Kevlar™-129 fabric, which is used to manufacture the DEA. This work contributes to the development of a robust shell-based model of the DEA. In the future, probabilistic methods will be used to quantify test-analysis correlation for the system-integrated models of helicopter crash impacts.

- A final task is to develop a system-integrated finite element model of the MD 530 helicopter, including accurate physical representations of the impact surface, skid gear, airframe, seats, occupants, restraints, cargo, ballast, and the external energy attenuating devices (airbags and the DEA). The model will be validated through extensive test-analysis correlation. Then, the validated model will be utilized to perform a complete risk assessment by evaluating different impact conditions, different impact attitudes, and multi-terrain.

The ongoing and planned research tasks being conducted within the SRW Aeronautics Research Program at NASA Langley are directly aimed at improving crash survivability of helicopters through the development of novel energy attenuating concepts and improved predictive capabilities. If successful, the program will demonstrate an alternative concept to external airbags for improved crash safety of the legacy fleet. It is anticipated that the research on predictive techniques for crash simulation will lead to increased confidence in the analytical methods, thereby encouraging greater use of crash simulation during the preliminary design phase of new aircraft.

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